Arm-wrist haptic sleeve for drone teleoperation

Vivek Ramachandran, Matteo Macchini, and Dario Floreano

***Abstract*—Teleoperators rely on both visual and haptic feedback to perform drone teleoperation tasks, such as obstacle avoidance. Haptic feedback becomes essential when visual feedback is compromised, either due to visual occlusions or poor depth perception. However, haptic interfaces, are often bulky because they require heavy actuators to provide force feedback. The bulkiness reduces user mobility and makes these interfaces unsuitable for prolonged use. Here, we propose a wearable haptic sleeve that encompasses the wrist and elbow joints of a human arm. The two joint rotations control the motion of a drone in a simulated environment along a horizontal plane. The sleeve is composed of modular electroadhesive clutches that block the joint movement when the drone is in the vicinity of an obstacle. The clutches are lightweight ($27\,\mathrm{g}$), require low power ($\sim 1\,\mathrm{mW}$) to operate, and can be mounted on the user without affecting the user's mobility. A motor learning subject study is conducted to navigate a drone through a hole in a wall where the depth perception of visual feedback is compromised. The results of the study show that subjects trained with the wearable haptic sleeve learnt the drone obstacle avoidance task and retained the necessary motor skills after haptic training, compared to subjects who received only visual feedback and were unable to learn the motor task.**

***Index Terms*—Wearable haptics, Textile devices, Human-robot interfaces, drone teleoperation**

I. Introduction

ROBOTS are increasingly becoming a quotidian presence in our surroundings, ranging from domestic floor cleaners to heavy construction machinery [1]. Drones in particular are used by a variety of people, including hobbyists for adventure photography and Search-and-Rescue professionals to inspect debris [2], [3]. While robot autonomy is a burgeoning area of research, presently, human operators are still needed to control distally - located robots for most tasks [4]. Indeed, teleoperation is the predominant method of operating drones for civilian applications and conventionally, they are operated using hand-held controllers, such as joysticks [2]. Professional pilots who are able to control drones effectively using these conventional controllers require a considerable amount of training to use them. However, these interfaces are not intuitive for novice users. The growing use of drones by non-professionals mandates more intuitive interfaces [5]. In recent years, researchers have developed wearable interfaces that map natural body movements to drone commands. These interfaces are more intuitive than hand-held controllers, provide a more immersive experience during teleoperation, and require very little time for users to train with [6].

Teleoperation using wearable interfaces, also called wearable teleoperation, of drones is bidirectional. The operator's body movements control drone motion and the robot provides information to the operator about its state and the state of its surroundings through sensory feedback [7], [8]. The sensory feedback is provided as some combination of three channels – visual, auditory, and haptic feedback. Distributing the information from the robot into multiple channels rather than concentrating it through one channel can help lower the cognitive load on the teleoperator [9], [10]. Visual feedback is often treated as the most essential feedback channel that determines the performance of teleoperation. Nonetheless, haptic feedback has specific benefits that can complement and/or supplement visual feedback [11]. For teleoperation training, wearable haptic interfaces, both tactile and kinesthetic, can apply targeted forces at specific parts of the operator's body that are responsible for the control of the robot to guide their body movement. Haptic feedback is vital when visual feedback is obscured either due to visual occlusions in the robot's environment or due to the operator's poor perception of depth [12].

Most haptic interfaces used for telerobotic applications are fixed to the ground [13]. As a result, they only allow users a limited range of motion and consequently, their applicability is limited too. Wearable haptic interfaces circumvent the problem of reduced mobility by being affixed to the user's body [14]. Amongst the soft, wearable haptic devices that have been developed in the past, some of them utilize jamming technologies powered by pneumatic energy, which often require the use of compressors or other pressure modulating auxiliary equipment [15]–[17]. Of the haptic devices used for teleoperation, many of them are functionalized gloves that provide feedback exclusively to the fingers of the hand [18]. The wearable haptic devices that are capable of providing kinesthetic feedback to the wrist and elbow joints of the arm employ the use of cables that are driven by electromagnetic motors, which need to be mounted on the user's body [19], [20]. The bulkiness and the form factor of these actuators re-introduces mobility problems and can cause fatigue over prolonged use. Actuated haptic interfaces are often used for haptic guidance-based training for teleoperation, a method that has been demonstrated to help users learn motor tasks in previous studies [21], [22]. However, these studies also suggest that trainees can become overly dependent on the haptic guidance. While their performance improves during training when they receive haptic feedback, this elevated performance precipitates when the haptic feedback is removed. In such cases, the haptic feedback becomes a crutch that curtails motor learning.

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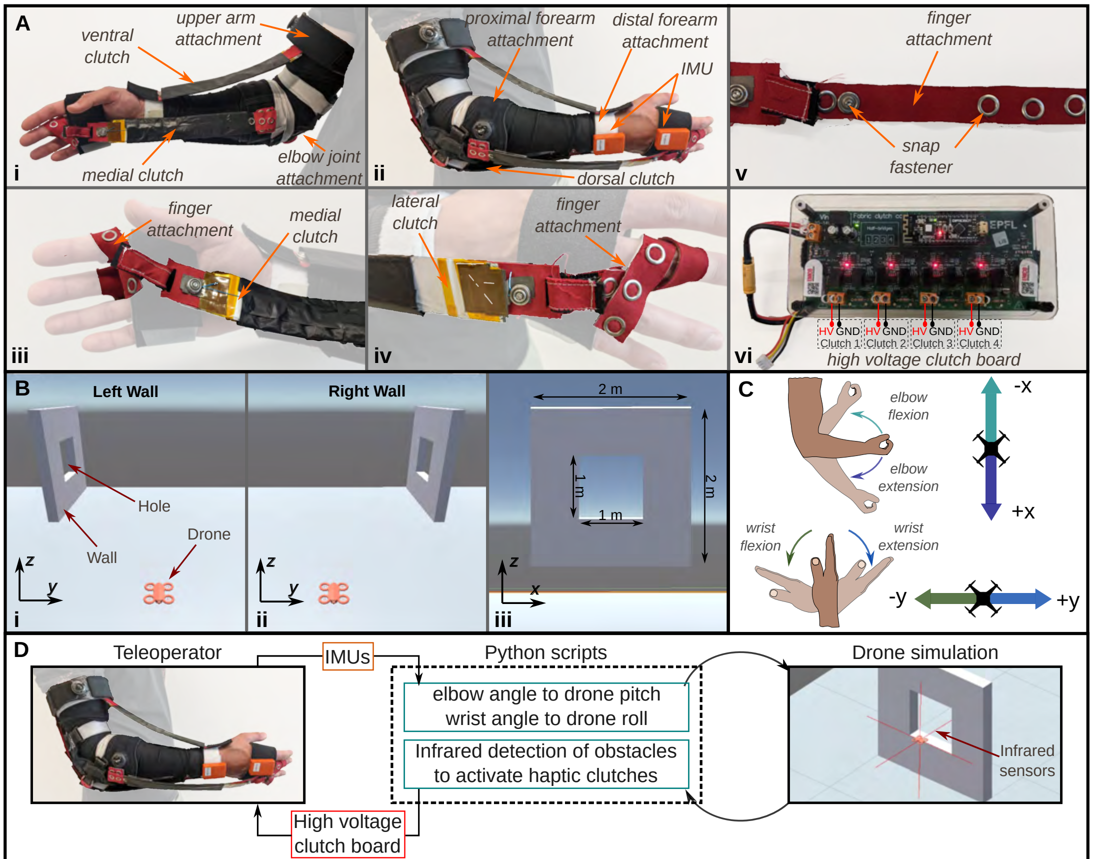

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type of feedback during human subject study - chronological order

group	baseline	training	evaluation
control	visual	visual	visual
test	visual	visual + haptic	visual

Figure 1: (A) The wearable haptic sleeve consists of four electroadhesive clutches to restrict elbow and wrist joint rotations. The clutches are mounted on the user using body attachments. The arm movements are measured using inertial measurement units (IMUs). The clutches are activated independently using a customised printed circuit board. (B) Wearable haptic sleeve to help users to perform obstacle avoidance during drone teleoperation. The obstacles are walls with a hole in the centre. (C) The drone is controlled through a linear mapping between the user's elbow and wrist joint angles and the drone's position in the horizontal plane. (D) A control pipeline describing the communication between the operator and the simulated robot. (E) The subjects are divided into two groups based on the the type of feedback that they receive. There are three experimental phases in the human subject study.

Recent studies show the use of lightweight, portable, tactile devices as very effective interfaces to perform teleoperation even when visual feedback is compromised [12], [23]. While these tactile haptic interfaces can indicate to the operator when they are in the vicinity of obstacles, these interfaces are not necessarily capable of completely arresting operator movement to prevent collisions from occurring, whereas kinesthetic haptic interfaces may be capable of doing so [18], [24], [25].

In our previous study, we successfully demonstrate the use of a lightweight, fabric-based wearable haptic sleeve that teaches users to perform a drone path following task [26]. The sleeve consists of two electroadhesive clutches attached to the ventral and dorsal faces of the human arm to restrict forearm extension and flexion about the elbow joint, respectively. Free of heavy actuators, the sleeve has a minimal effect on the user's natural mobility. In the study, the users who receive haptic feedback from the sleeve are able to learn and retain motor skills to perform the path following task, whereas the control group of users who only receive visual feedback from the drone's camera are unable to learn the task within the same time. We conclude that due to the absence of actuators, users are compelled to identify and correct their errors by themselves without becoming overtly dependent on the feedback.

In this letter, we demonstrate the use of the wearable haptic sleeve that consists of a network of clutches and attachments to block both the extension and flexion of the wrist and elbow joints. The sleeve is used to train users in a drone obstacle task, where the visual feedback is compromised due to poor depth perception. In other words, the purpose of the earlier study [26] is to examine the benefits of haptic feedback as an additional form of feedback to visual feedback whereas, the study in this letter evaluates the effectiveness of haptic feedback as a supplement to weak visual feedback. The sleeve presented in this letter helps users perform better by diminishing the number of obstacle collisions during training and facilitates skill retention in the absence of haptic feedback post-training.

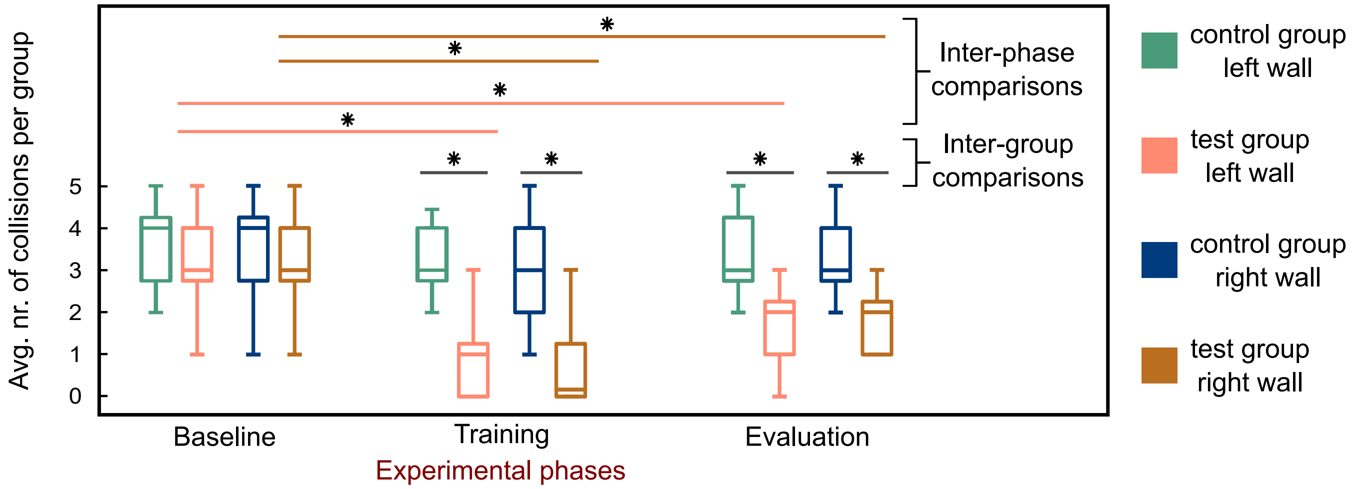

Figure 2: The control and test group performances are measured by computing the median number of collisions that take place per group. These data sets are compared by examining the differences between groups for the same wall in each phase, between walls for the same group in each phase, and between phases for the same group and same wall. $*p < 0.05$

II. Method

In this section, we present the different parts that constitute the experimental study: the design and operation of the wearable haptic sleeve (Section II-A), the setup of the simulation environment to perform teleoperation (Section II-B), and the human subject study to determine the effects of the haptic sleeve on training users to avoid obstacles during teleoperation with limited visual feedback (Section II-C).

A. *Wearable haptic sleeve*

1) Device design and operation: The sleeve is programmed to restrict the motion of both the elbow and wrist joints. The wearable haptic sleeve consists of four identical electrostatic adhesive clutches - one pair of clutches to restrict the forearm extension and flexion about the elbow joint and a second pair of clutches to restrict the hand extension and flexion about the wrist joint (see Fig. 1A). This sleeve is an extension of our previous wearable sleeve that was developed to restrict elbow joint rotation alone. The manufacturing method of the clutches used for the sleeve in this letter are adapted directly from our previous study [26].

Each clutch is a parallel plate capacitor with four interleaved electrode pairs. Each of the electrodes are metalized biaxially oriented polyethylene terephthalate sheets and they are coated with a layer of high-κ dielectric ink, a ferroelectric composition of barium titanate and titanium dioxide (Luxprint 8153, DuPont). The dielectric ink is cast on the electrodes and cured at $140\,°\mathrm{C}$ for sixty minutes in an oven. The final thickness of the solid dielectric that remains is $10\,\mathrm{mm}$ thick. The nonmetalized surface of each electrode is bonded to a $120\,\mathrm{mm}$ sheet of polymethyl methacrylate (PMMA). The overlapping pairs of electrodes are arranged in an interdigitated architecture. When a high voltage ($\sim$300V) is applied across the electrodes, an electric field is generated between the plates, which causes the plates to adhere to each other. In this state, the clutch is said to be activated. This electrostatic adhesion results in a rapid increase in the tensile stiffness that prevents longitudinal extension. The clutch also consists of a low-stiffness spring in parallel with the interleaved electrodes. When the clutch is deactivated i.e., the applied voltage is set to zero, the interleaved plates can freely slide on top of each other. In this state, the tensile stiffness of the clutch is determined only by the spring stiffness. The electromechanical properties of the clutch are reported in our previous study [26].

The clutches are mounted on the human arm using body attachments (see Fig. 1A). The elbow clutches require three attachments – distal forearm, upper arm, and elbow joint. The distal forearm and upper arm attachments are used to anchor the ventral and dorsal clutches to block the elbow joint. The elbow joint attachment ensures that the dorsal elbow clutch does not slip out from under the elbow during forearm flexion. The distal forearm attachment and the upper arm attachments are fabricated by coating long strips of elastane on one face with silicone rubber and adhering a strip of loop-type Velcro on the other face. The silicone rubber is used to interface with the human skin because it is comfortable In addition, an adjustable BOA tightening custom dial strap is used to secure the anchoring of the clutch on the upper arm attachment. The ventral and dorsal clutches have strips of Hook-type fastener that attaches to the Loop-type fastener on the distal forearm attachment and the upper arm attachment.

The clutches fabricated for the wrist joint are identical in nearly all respects to the clutches fabricated for the elbow joint [26]. However, the body attachments required for the wrist joint are completely different. Therefore, the ends of the wrist clutches were modified to comply with their corresponding body attachments. The wrist clutches, lateral and medial, responsible for restricting the wrist joint, require two attachments – proximal forearm and finger (see Fig. 1A-i,ii,iii,iv). The proximal forearm attachment is an adjustable elbow brace with a BOA tightening system and a Loop-type fastener exterior. The finger attachment is a fabric strip coated with the silicone rubber that can be wound around the index finger and adjusted to the length of the user's hand using Hook-and-Loop fasteners and snap fasteners (see Fig. 1A-v). Both

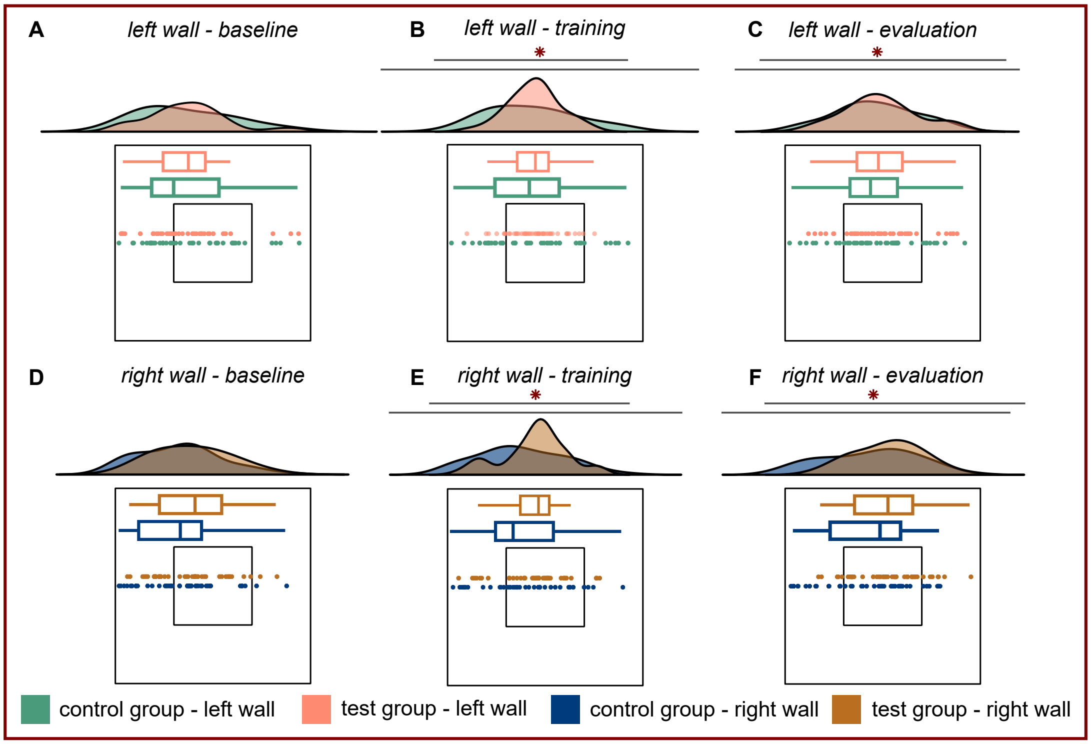

Figure 3: The variances of the drone position relative to the wall are compared at the time instant the drone either collides with the wall or passes through the hole. Comparisons are carried out for the (A-C) left wall and (D-F) the right wall between the control and test groups for the baseline, training, and evaluation phases. $*p < 0.05$

the lateral and medial clutches are fabricated with Hook-type fasteners that mate with the Loop-type fastener exterior on the proximal forearm attachment. The wrist and elbow angles are measured using commercially available inertial measurement units (Xsens IMUs), which are mounted on the distal forearm attachment and a stretchable Velcro strap that is wrapped around the user's palm.

2) Driving electronics: Each of the four clutches are activated using a custom designed printed circuit board that requires a $12\,\mathrm{V}$ power supply, which is typically provided by a 3-cell Lithium-Ion battery (see Fig. 1A-vi). The board consists of four H-bridges - well known transistor configurations to drive a bidirectional load from a single power source. Each H-bridge has two independently controlled outputs. Hence, each of the four clutches can be connected either between an output and a ground (for a unidirectional drive) or between two outputs (for a bidirectional drive). When one of the H-bridge outputs is switched on, a high voltage (HV to GND) is applied across the clutch connected to activate it. The high voltage is generated using a commercially available high voltage DC-DC converter (EMCO A04P-5). A microcontroller (DFROBOT Bluno Nano V1.4) that operates the H-bridge switching, can be controlled over Bluetooth by means of simple ASCII-based commands ('1', '2', '3', '4') to activate the corresponding clutches. The board is designed to be completely portable, such that users would be free to move unrestricted by cables.

B. Simulation environment

Users are trained to perform a drone-obstacle avoidance task in a simulated environment. For our study, we adapted the simulation environment implemented in Unity3D from recent work carried out by colleagues [12]. Within the environment is a drone that reproduces quadcopter dynamics, which is stabilised using a PID controller (see Fig. 1B). This drone spawns at an initial height of $1\,\mathrm{m}$ above the ground. We choose a one-to-one mapping between the user's arm motion and the drone's motion. Since the haptic system is designed to block the elbow and wrist joints, the drone's motion is restricted to the two-dimensional horizontal plane while preserving rigid body dynamics of the drone in that plane. The user's wrist and elbow joint angles are mapped linearly to the drone's position (see Fig. 1C). Hand extension and flexion about the wrist joint makes the drone roll to the right and left respectively. Similarly, forearm extension and flexion about the elbow joint pitches the drone forward and backward respectively. The change in wrist and elbow joint angles are measured using commercially available inertial measurement units (Xsens IMUs) mounted on the hand and the forearm (see Fig. 1D). The linear scaling factor from the joint angles to the drone's position is chosen such that the user can teleoperate the drone anywhere within the environment. The drone's height is constrained to remain at a constant height above the ground. Each drone is equipped with orthogonal proximity sensors with a fixed range of $0.7\,\mathrm{m}$. For most inspection tasks in confined spaces, drones need to be navigated around walls and through narrow passages without collisions. The teleoperation task chosen for user training incorporates certain aspects of these inspection tasks. A wall with a hole is placed perpendicular to the line of sight of the user, such that the user is unable to clearly determine the location and dimensions of the hole in the wall (see Fig. 1B). Shadows are not rendered

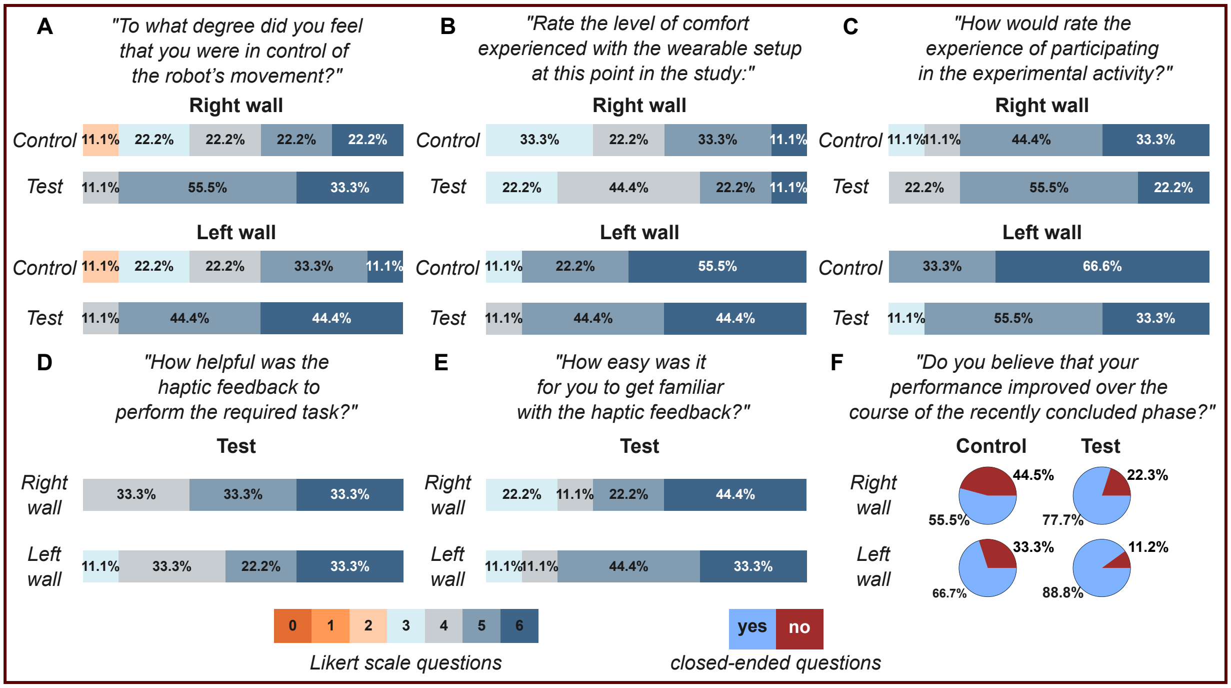

Figure 4: Subjects respond to a customised questionnaire that factors in qualitative experiences pertaining to (A) degree of drone control, (B) comfort level with wearable setup, (C) overall participation using a Likert scale. Specific questions were posed to test group subjects to determine the (D) helpfulness and (E) familiarity with the haptic feedback that they received. (F) Subjects in both groups were asked to self-assess their performance improvement in a closed question.

in the simulation environment to avoid giving fiducial features that might help users ascertain the depth of the wall relative to the location of the drone. The environment has a fixed camera perspective that is relayed to the user as visual feedback during teleoperation. If the drone collides with the wall at any point of time during teleoperation, the wall colour changes to red. If the drone is steered through the hole without colliding with the wall, the wall colour changes to green. Previous psychophysical studies show a relative difference in comfort and strength between hand extension and hand flexion about the wrist joint. Hence, two walls are created - on the left-hand side (*left wall*) and right-hand side (*right wall*) of the user's line of sight to examine any potential differences in their performance. The teleoperation training for one wall is completed before commencing training for the second wall.

C. Human subject study

A total of 18 adult subjects (ages between 22 and 31; mean = 25.94, standard deviation = 2.79) are recruited for a human subject study to investigate the effect of the wearable haptic sleeve on training users to teleoperate drone through narrow passages with reduced visual feedback. Each of the subjects in this study are healthy, have normal or corrected-to-normal vision, and are right-handed. The subjects provide written informed consent, and the study is approved by the EPFL Human Research Ethics Commission. In chronological order, the task consists of three experimental phases – baseline, training, and evaluation for navigating the drone through the hole in the left wall and the right wall separately using their right-arm's elbow and wrist joint rotations (see Fig. 1D). The order of the walls, left wall and right wall, is randomized to prevent any biasing effects. Each phase consists of five sessions, which end when the subjects either collides with the wall or passes through the hole. At the commencement of the study, the subjects are explicitly instructed to minimize the number of collisions during drone teleoperation. The subjects are divided into two groups – control and test. Both groups receive visual feedback from a fixed camera perspective that shows the drone and the wall during all three experimental phases for both the left and right walls. While subjects in both groups don the wearable sleeve during the subject study, only subjects in the test group receive haptic feedback from the sleeve during the training sessions. Subjects in the control group continue to receive only visual feedback from the fixed camera. Haptic feedback is provided to the test group subjects during the training phase when the proximity sensors on the drone detect the presence of the wall. When the wall is detected by simulated infrared proximity sensors on the drone, only the clutch needed to restrict the specific joint movement to prevent wall collisions is activated using the high voltage clutch board (see Fig. 1D). Since the haptic feedback to block user movement is provided only when the drone is in the proximity of the wall, we do not attribute any mechanical properties such as elasticity to the wall itself. Hence, if the drone collides with the wall, the user does not experience any haptic feedback. The subject performance is determined by the average number of drone collisions that occur over the sessions of each phase. As terminal visual feedback, the success or failure for each experimental session is indicated by the wall turning green (passage through hole) or red (wall collision) respectively. In addition, the relative position of the drone with respect to the wall is measured when the drone either passes through the holes or collides with the wall for all phases. A comparative study is made between the test and control groups for each wall as well as for each group between the left and right walls using the aforementioned performance metrics. After performing the teleoperation task phases for each wall, subjects are asked to fill two surveys - one standardised NASA-TLX questionnaire and one customised questionnaire to determine their experience of wearing the haptic sleeve.

III. Results

In this section, we summarise the results of the human subject study that examined the effects of haptic feedback as a teaching aid during drone obstacle avoidance tasks when visual feedback was compromised. The section is divided into two parts. Firstly, we provide a comparative performance analysis of the control group and the test group over the experimental phases for each wall (Section III-A). Secondly, we present the qualitative experiences of subjects in each group based on the data collected from the two questionnaires (Section III-B).

The Shapiro-Wilk statistical test of normality is performed on all the subject data sets. Since some of these data sets are not normally distributed, we decide to use non-parametric statistical tests of significance to analyse the subject data. Comparisons are made between the subjects' median data using the Kruskal-Wallis test. For each group, comparisons of median data between phases are carried out by the Friedman test. Furthermore, the variances of the data sets of each group for each phase are compared using the Levene test. All the TLX questionnaire responses are compared pairwise using the Kruskal-Wallis test. The null hypothesis for each statistical test of significance is rejected when $p < 0.05$.

A. Performance analysis of obstacle avoidance

Each subject is required to perform the obstacle avoidance task for five sessions in each experimental phase. Hence, their individual performance for that phase is determined by taking the mean number of collisions over the five sessions. For each wall, the group performance for a particular phase is measured by calculating the median value of the individual performances of that phase see Fig. 2. The Friedman test followed by a *post-hoc* Bonferroni correction shows that there is a statically significant difference in the test group's performance between the training and baseline phases as well as between evaluation and baseline phases, but not between the training and evaluation phases for each wall. The same statistical tests show no significant differences in performance between the different phases for the control group for either wall (left wall: $p = 0.88$; right wall: $p = 0.36$). This clearly shows that subjects who receive haptic feedback from the wearable sleeve improve their performance over the course of the training phase and maintain their performance level during the evaluation phase, even in the absence of the haptic feedback. On the other hand, subjects who only receive the visual feedback over the course of all the three experimental phases are unable to correct their errors and their performance do not improve. For both walls, the Kruskal Wallis test shows no statistical differences in baseline performances between the control and test groups for either wall (left wall: $p = 0.46$, right wall: $p = 0.38$). However, the same test reveal statistical differences between the control and test groups for both wall during the training and experimental phases. These results corroborate our earlier observation that the wearable haptic sleeve is a useful aid for operators to avoid drone collisions, especially when the visual feedback is compromised. There are no measured statistical differences in performance between the left wall and the right wall for either group during any of the phases (baseline, control: $p = 0.94$, test: $p = 0.98$; training, control: $p = 0.84$, test: $p = 0.84$; evaluation, control: $p = 0.93$, test: $p = 0.1$).

We also compare the subject data sets of the drone's position along the face of the wall at the time when the drone either collided with it or passed through the hole (see Fig. 3). The Kruskal Wallis test does not show any significant differences in the median values between the control and test groups for any of the phases in either wall (left wall, baseline: $p = 0.56$, training: $p = 0.5$, evaluation: $p = 0.07$, right wall, baseline: $p = 0.13$, training: $p = 0.06$, evaluation: $p = 0.97$). It does not show significant differences in the median values for the same group and same phase between the left and right walls either (baseline, control: $p = 0.59$, test: $p = 0.64$; training, control: $p = 0.36$, test: $p = 0.64$; evaluation, control: $p = 0.54$, test: $p = 0.24$). The Levene test for comparing variances does not show significant differences in the variance between the control and test groups for the baseline phase for either wall (left wall: $p = 0.43$, right wall: $p = 0.33$; see Fig. 3A,D). The Levene test shows that there is a significant difference between the groups for both the training and evaluation phases for both walls (see Fig. 3B,C,E,F). This suggests that not only does the haptic feedback help test group subjects make fewer drone collisions, it also helps them significantly narrow the margin of error as is evident in the smaller spread of data points along the wall compared to their control group counterparts. The Levene test followed by a *post-hoc* Bonferroni correction shows that there is a statically significant difference in the test group's variance between the training and baseline phases as well as between evaluation and baseline phases, but not between the training and evaluation phases for each wall. The Levene test shows that there is no statistically significant difference in the control group's variance between any of the three phases for each wall (left wall: $p = 0.88$, right wall: $p = 0.36$).

B. Questionnaire responses

The results of the customised questionnaire ascertain the subjects' experiences of comfort in performing the teleoperation task while wearing the haptic sleeve (see Fig. 4). This questionnaire consists of 6 questions, 5 of which are Likert scale questions (0 to 6) and 1 is closed question (yes/no). At the end of the experiment, only $66.6\,\%$ of the control group subjects feel that they had been in control of the robot's movement for both walls (between 4 and 6) whereas $100\,\%$ of the test group subjects feel that they had complete control (see Fig. 4A). For the left wall, $100\,\%$ of the subjects from the test group and $88.8\,\%$ from the control group rate the sleeve's level of comfort between 4 and 6 (see Fig. 4B).

However, for the right wall, a relatively lower percent of the subjects rate the sleeve's level of comfort between 4 and 6 ($77.7\,\%$ test group, $66.6\,\%$ control group). The results from both questions allow us to posit that the subjects' ability to control the robot does not necessarily depend upon the location of the wall, but the sleeve appears to cause discomfort when subjects' have to extend their wrist. For the test group subjects, $100\,\%$ of the subjects find the haptic feedback helpful (between 4 and 6) for the right wall and $88.8\,\%$ find it helpful for the left wall (see Fig. 4D). At the same time, only $77.7\,\%$ of those subjects find the haptic feedback easy to become familiar with for the right wall (between 4 and 6) compared to $88.8\,\%$ of them who are able to become familiar with it with the left wall (see Fig. 4E). Furthermore, $88.8\,\%$ and $77.7\,\%$ of test group subjects positively assess an improvement in performance over the course of the experimental phases for the left and right walls respectively (see Fig. 4F). A lower percentage of control group subjects - $66.6\,\%$ for left wall and $55.5\,\%$ for right wall - positively assess an improvement in their performance. These responses indicate that while tasks that require wrist flexion might be easier to perform than those that require wrist extension, additional haptic feedback could make the task easier to perform for both wrist flexion and wrist extension. Not all test group subjects are able to familiarize themselves with the haptic feedback that they were receiving. Nonetheless, a large percentage of test group subjects feel that their performance had improved as a result of the haptic feedback compared to a lower percentage of control group subjects. Finally, at least $88.8\,\%$ of all subjects for both walls positively rate their experience of having participated in the experimental activity (between 4 and 6) (see Fig. 4C).

The NASA-TLX test is used to assess various qualitative aspects of subjects participating in the study, including the amount of mental, physical, and temporal demands, the amount of effort expended, and the level of frustration experiences (see Fig. 5). There are no observable significant differences in the amount of mental demand between the control and test groups for the left wall or the right wall as per the Kruskal-Wallis test (left wall: p = 0.89; right wall: p = 0.53; see Fig. 5A). In addition, there are no observable significant differences in the amount of mental demand for each group between the left and right walls (control: p = 0.53; test: p = 0.85). However, upon comparing the median values, it is worth noting that the control group find the task more mentally demanding when performing the task with the right wall than the left wall. The task is significantly more physically demanding for control group subjects than for test group subjects for both walls (see Fig. 5B). Neither of the groups find the the task with either wall significantly more physically demanding than the other, but similar to the mental demand data, the median value for the control group with the right wall is higher than for the left wall (control: p = 0.26; test: p = 0.68). There are no significant differences in the temporal demand between the control group and test group for either wall (left wall: p = 0.65; right wall: p = 0.09, see Fig. 5C) or for each group between either wall (control: p = 0.96; test: p = 0.19). The test group subjects expend significantly lesser effort than control group subjects for both walls (see Fig. 5D). This is indicative of the benefits of the haptic feedback when visual feedback is compromised. Although there are no significant differences in the amount of effort expended by either group between each wall (control: p = 0.59; test: p = 0.24), the median value is lower for both the control and test groups for the left wall compared to the right. There are no significant differences in the level of frustration experienced between the test and groups for either wall (left wall: p = 0.75; right wall: p = 0.24; see Fig. 5E) or for each group between either wall (control: p = 0.19; test: p = 0.82).

IV. Conclusions

We present a wearable haptic sleeve that provides kinesthetic feedback to help users avoid obstacles during a drone teleoperation task when the visual feedback provided to the users is poor. The sleeve reduces errors by blocking the subjects' wrist and elbow joints when the drone is in the vicinity of an obstacle. Test group subjects, who receive the haptic feedback during the training phase of the experiment, make fewer errors than control group subjects. The test group subjects also make fewer errors than the control group subjects during the evaluation phase when the haptic feedback is no longer provided. These results show that subjects trained with the haptic feedback are able to learn the activity and retain the necessary motor skills without becoming overly dependent on the feedback. While there are no statistically significant differences in the performance for each group between the left and right walls for any of the phases, certain qualitative differences were observed in the questionnaire data. These differences are especially noticeable for the control group subjects who require a higher mental demand and expend a larger amount of effort for performing the task with the right wall than for the left wall. The higher mental demand and effort can be attributed to the relative discomfort in the extension of their wrist compared to flexion. All subjects in the study are right-handed and they use their right arm to don the wearable haptic sleeve and teleoperate the drone.

This work is a demonstration of the scalability of the wearable haptic sleeve to multiple body joints. Each antagonistic clutch pair corresponding to one joint operates independent of the clutch pair for the other joint. The absence of bulky actuators makes this lightweight sleeve both portable and unobtrusive to natural human mobility when haptic feedback is not provided. While the sleeve should be capable of preventing all drone collisions with obstacles, we need to acknowledge the presence of errors that are caused due to a combination of hasty subject movement and latencies introduced by drone dynamics. These errors can be further reduced by tuning the controller gains to improve the drone responsiveness to user movement. Further experiments are needed to explore the use of the wearable haptic sleeve to teleoperate multi-agent systems, such as swarms of drones when they pass through narrow spaces without the agents colliding with each other or the surrounding environment. There is promise in investigating the use of the wearable haptic sleeve for controlling robots apart from drones. For instance, the fabric-based electroadhesive clutches can be integrated

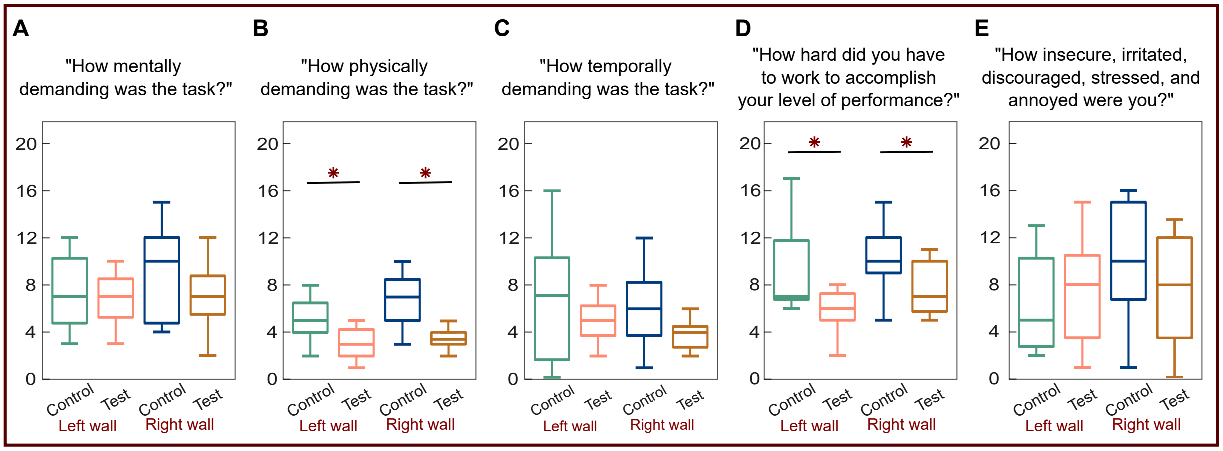

Figure 5: Subjects provide their responses to a NASA-TLX questionnaire that evaluates their work load as a participant through standard metrics. $*p < 0.05$

in clothing-like rehabilitative devices that require intentional body movement restriction as part of patient therapy. Another field of application is Search-and-Rescue robotics – rescue personnel, who are untrained in robotic teleoperation, can use the haptic sleeve to control different types of rescue robots using intuitive body gestures and receive feedback in case the robot is at risk of colliding with obstacles. A full-body haptic suit with electroadhesive clutches may also be used for facilitating greater human-human interaction and collaboration between individuals situated in distant locations. Indeed, such a suit could also be used to perform motor tasks, including dancing, playing instruments, and assisting in the manual handling of heavy objects.

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